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Dan Holiday, Gregory Carter, Richard W. Gould, Hugh MacIntyre

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14. ABSTRACT
This study investigates the use of satellite remote sensing to detect blooms & predict environmental conditions leading to the formation of HAVs in the turbid coastal waters along the Mississippi and Alabama shores. Phytoplankton populations and in situ water quality were monitored at 3 to 6 week intervals at 17 locations in Mobile Bay & the Mississippi Sound beginning in July, 2005 & continuing thru June, 2006 along w/ concurrent MODIS Aqua weekly composite or same-day imagery. In situ or satellite-derived water properties included surface temperature, salinity, Chla, TSS, CDOM, & nutrient levels. Simple curvilinear & multiple stepwise regressions determined relationships between phytoplankton cell counts & water properties. These results are being used to develop a prediction model for HABs in coastal water of the northern Gulf of Mexico based on daily to weekly satellite observations.

15. SUBJECT TERMS
MODIS, Aqua , Terra, Gulf of Mexico, Mississippi Bight, HABs, predictive modeling

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Harmful Algal Blooms in the Mississippi Sound and Mobile Bay: Using MODIS Aqua and In Situ Data for HABs in the Northern Gulf of Mexico

D. Holiday [a], G. Carter [a,*], R. Gould [b], H. MacIntyre [c]

[a] Gulf Coast Geospatial Center, University of Southern Mississippi, Ocean Springs, MS 39564 – (dan.holiday, greg.carter)@usm.edu
[b] Naval Research Laboratory, Code 7333 Ocean Optics, Stennis Space Center, MS, 39529 – rgould@nrlssc.navy.mil
[c] Dauphin Island Sea Lab, Dauphin Island, AL, 36528 – hmacintyre@www.disl.org

Abstract - This study investigates the use of satellite remote sensing (MODIS Aqua sensor) to detect blooms and predict environmental conditions leading to the formation of HABs in the turbid coastal waters along the Mississippi and Alabama shores. Phytoplankton populations and in situ water quality were monitored at 3 to 6 week intervals at 17 locations in Mobile Bay and the Mississippi Sound beginning in July, 2005 and continuing through June, 2006 along with concurrent MODIS Aqua weekly composite or same-day imagery. In situ or satellite-derived water properties included surface temperature, salinity, chlorophyll-a concentrations (Chl*a*), total suspended solids (TSS), chromatophoric dissolved organic material (CDOM), and nutrient levels (nitrates and nitrites (no3no2), organic and inorganic carbon, nitrogen, and phosphates). Simple curvilinear and multiple stepwise regressions determined relationships between phytoplankton cell counts and water properties (both directly measured and satellite-derived). In general, counts of dinoflagellates correlated positively with temperature (r-squared = 0.17 to 0.73) and Chl*a* (r-squared = 0.11 to 0.82), while diatoms tended to exhibit inverse relationships with temperature and salinity. Multiple stepwise regression analyses suggest Chl*a*, surface temperature and salinity as primary factors in population levels. These results are being used to develop a prediction model for HABs in coastal waters of the northern Gulf of Mexico based on daily to weekly satellite observations.

Keywords: MODIS, Aqua, Terra, Gulf of Mexico, Mississippi Bight, HABs, predictive modeling.

1. Introduction

Harmful algal blooms (HABs) are proliferations of microalgae accumulating at biomass levels that negatively affect co-occurring organisms and the food web. Some HAB species produce toxins that bioaccumulate in shellfish and fish. Others proliferate in response to changing environmental conditions, such as nutrient flux and eutrophication, creating hypoxic or anoxic conditions (Anderson *et al.*, 2002). Over the past several decades, the frequency and severity of HABs has increased in USA coastal areas. In some regions, blooms of harmful microalgal species have resulted in the collapse of ecosystem processes due to environmental stress. At the same time, they have caused regional economic losses of 10 to 200 million dollars annually (Hoagland and Scatasta, 2006) due to human health problems, commercial and recreational fishing closures, and cleanup costs. Remote sensing has shown potential toward the mitigation of such ecological and economic losses (Stumpf, 2001; Stumpf *et al.*, 2003). The use of satellite sensors such as the MODerate-resolution Imaging Spectroradiometer (MODIS) enables twice daily (MODIS Aqua PM and MODIS Terra AM), wide area coverage not economically possible with traditional ship and shore survey techniques (Tatem *et al.*, 2004). The purpose of this study is to evaluate the use of MODIS data for detection of HABs and the prediction of ecological conditions leading to their formation in the turbid waters of the northern Gulf of Mexico (GOM).

Surveys carried out in Alabama waters by Pennock, *et al.*, in 2001 and 2002 and routine surveys done by Dauphin Island Sea Lab (DISL) and the Alabama Department of Public Health (ADPH) regularly identify species of microalgae, mostly dinoflagellates and diatoms, with the potential to create HAB events. To date, 5 known HAB species have been detected at significant levels (>10^5 cells L^{-1}) in coastal waters of the northern GOM. These include the diatoms *Pseudo-nitzschia* spp and the dinoflagellates *Karenia brevis*, *Gymnodinium sanguineum*, *Dinophysis caudata*, and *Prorocentrum minimum*. *Pseudo-nitzschia* produces domoic acid, the causative agent in amnesiac shellfish poisoning (ASP). *Karenia*, *Gymnodinium*, and *Dinophysis* produce brevitoxin, saxitoxins, and okadaic acid, respectively, while in turn these toxins are responsible for neurotoxic, paralytic, and diarrhetic shellfish poisoning (NSP, PSP, and DSP) (Landsberg, 2002). *Prorocentrum minimum* is a cosmopolitan species reported by Steidinger and Tangen (1996) to be toxic in Florida, USA, waters. Other potential HAB species, such as the dinoflagellates *Karenia mikimotoi*, associated with massive fish kills in Japan and Korea, and *Gonyaulax polygramma*, associated with non-toxic red tides in Florida (Landsberg, 2002) have been found at low levels (<2000 cells L^{-1}) in surveys of Mobile Bay that are regularly carried out by DISL and the ADPH. As human populations increase in the Mobile Bay and Mississippi Sound regions, anthropogenic nutrient loading will rise correspondingly. Anderson *et al.*, (2002) showed that increase in coastal water nutrient loads correlated directly with increased microalgal populations, demonstrating a need for economical and efficient means of HAB detection and prediction in the northern GOM.

2. Materials and Methods

2.1 In Situ Sampling

Surface water samples were collected at 3-6 week intervals from July, 2005 through June, 2006 at 12 stations in Mobile Bay and 5 stations in the Mississippi Sound (Figure 1). Taxa and cell count data for phytoplankton populations were

*Corresponding author.

analyzed by the ADPH. Sea surface readings of temperature and salinity were recorded for each station.

Figure 1. MODIS 250m resolution greyscale image showing locations of collection sites in Mobile Bay and the Mississippi Sound.

A full description of the physical and optical hydrography at each Mobile Bay site was done by DISL at the time of sampling. This included vertical description of sea surface temperature (SST), salinity (PPT), pH and dissolved oxygen from a CTD (SeaBird SBE16); spectral absorption and scattering (ac-9), Chromatophoric Dissolved Organic Matter (CDOM) and Chl*a* fluorescence (WETStar and SeaPoint Sensors fluorometers), and spectral downwelling and upwelling irradiance and radiance (Satlantic MicroPro). Discrete samples were collected from both the MS Sound and Mobile Bay for laboratory analysis of optical characterization (spectral absorption by microalgae, detritus and CDOM), microalgal abundance and taxonomic distribution (using abundance of marker pigments), particulate loading (particulate C, N and P, seston) and nutrient concentrations (dissolved inorganic carbon, nitrogen, and phosphorous (DIC, DIN and DIP), with DIN estimated as the sum of nitrate plus nitrite and ammonium, dissolved organic carbon, nitrogen, and phosphorous (DOC, DON and DOP).

2.2 Remote Sensing Data

Daily and weekly composite MODIS Aqua and Terra imagery at 1km resolution encompassing the Mississippi Bight region in the northern Gulf of Mexico were acquired from the Naval Research Laboratory (NRL) Oceanography Division at Stennis Space Center, Mississippi. The NRL has developed refined MODIS algorithms tailored for turbid coastal waters. MODIS-derived data products include SST, Chl*a* (oc3m algorithm), Particulate Organic Matter concentration (POM), Particulate Inorganic Matter concentration (PIM), Total Suspended Solids concentration (TSS), CDOM absorption (at 412 nm), detrital absorption (at 412 nm), phytoplankton absorption (at 443 nm), backscattering coefficient (at 555 nm), and remote sensing reflectance at 6 wavelengths.

2.3 Data Analysis

Nutrient and environmental data from MODIS data products received from the NRL and in situ data from the Mobile Bay and Mississippi Sound collection sites were correlated using simple regression analyses (SAS v6.12, SAS Institute, Cary, NC). Stepwise regression analyses were performed to determine relationships between population data from in situ collections. Independent variables included SST, PPT, Chl*a*, TSS, and no3no2. The nutrient data were chosen due to their importance in phytoplankton population cycles and eutrophication of estuaries (Anderson *et al.*, 2002) as well as their predictabilities from MODIS data. These analyses provide a baseline for the development of HAB prediction models given satellite-derived water conditions.

3. Results and Discussion

All MODIS-derived values exhibited linear relationships when compared with in situ measurements. The strongest relationship (r^2= 0.9543) was observed between MODIS-derived and in situ SST (Figure 2). Surface temperature readings, both water and land, are one of the principal objectives of the MODIS sensor (Tatem *et al.*, 2004) on the Aqua and Terra platforms. The temporal and spatial coverage provided by their twice daily passage over the earth's surface are essential to long-term monitoring of environmental status and change, with surface temperature being a vital aspect of these studies (Wan *et al*, 2004). Linear relationships of in situ Chl*a* and TSS with MODIS Chla and TSS data products (r^2= 0.3299 and r^2= 0.2067 respectively) were also significant.

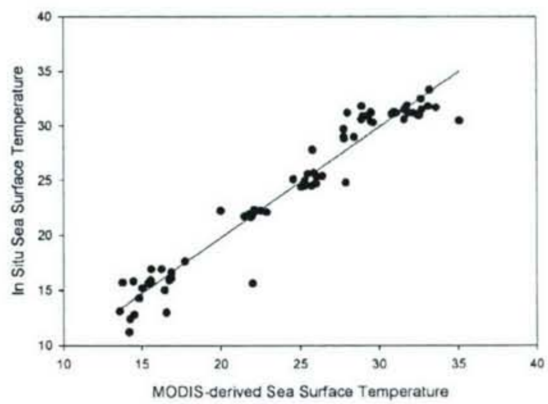

Figure 2. In Situ vs. MODIS sea surface temperature (r^2= 0.9543).

Phytoplankton population surveys showed high diversity, with samples often being comprised of tens of genera and more than 100 species. Collections represented 13 phyla and 95 genera. However, some species were observed at notably greater frequency and in higher numbers. These included the dinoflagellates *Scripsiella trochoidea*, *Gonyaulax digitale*, *Heterocapsa triquetra*, *Katodinium glaucum* and *Karenia brevis* and the diatoms *Pseudo-nitzschia* spp., *Chaetoceros* spp., *Pleurosigma* spp. and *Nitzschia* spp.. Further analyses focused on these taxa due to their high rate of occurrence in

sampling (range= 18 – 112), taxonomic relationship with known HAB species and relations between species occurrence and nutrient data (Table 1). Populations of Chlorophytes, Cryptophytes, and Cyanophytes exhibited seasonal dominance and normally occur in freshwater. Their presence in GOM samples was in response to seasonal cycles of rainfall and runoff into the GOM. Thus, these taxonomic groups were excluded from further analysis.

Species	Variable	r^2	n
Gonyaulax digitale	Chl*a*	0.9228	18
Heterocapsa triquetra	Chl*a*	0.826	18
Katodinium glaucum	SST	0.1963	65
Karenia brevis	Chl*a*	0.4756	25
Scripsiella trochoidea	Chl*a*	0.675	67
Chaetoceros	PPT	0.0933	88
Pleurosigma	SST	0.263	112
Pseudo-nitzschia	PPT	0.0591	93
Nitzschia	Chl*a*	0.5694	41

Table 1. Linear relationships between population cell count and water quality variables measured in situ (n= number of samples).

Diatom populations tend to exhibit inverse relationships with salinity and temperature, while dinoflagellates tend to exhibit positive relationships with PPT and Chl*a*, such as *Heterocapsa triquetra* with Chl*a* (Figure 3).

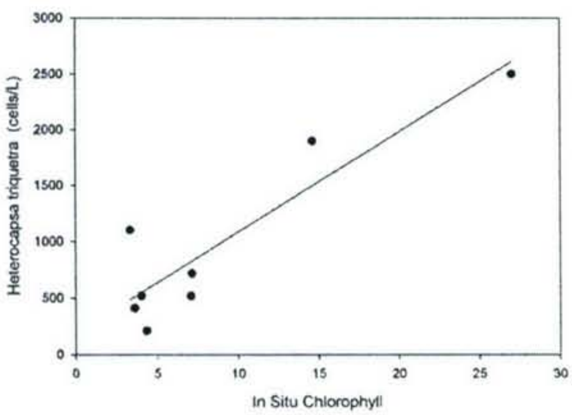

Figure 3. *Heterocapsa triquetra* cell count vs. Chl*a* (r2= 0.826).

The low correlations exhibited in relationships between phytoplankton and in situ data illustrate information useful to interpretation of data. The diatom genus *Pseudo-nitzschia*, while exhibiting a low correlation with SST (r^2= 0.0591), also exhibited a distribution peak (Figure 4), indicating potential for population blooms at a range of 20-22 SST.

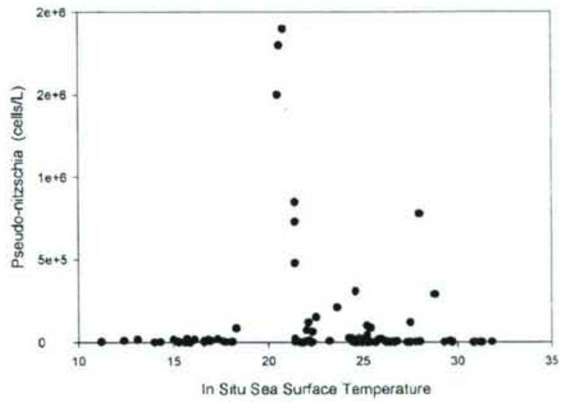

Figure 4. *Pseudo-nitzschia* cell count vs. SST. Note apparent optimum at 20-22° C.

4. Conclusions

Initial regression analyses suggested strong relationships between phytoplankton species shown in Table 1 and in situ variables SST, PPT, TSS, CDOM and no3no2. These simple analytical techniques were expanded using multiple stepwise regression analyses. Results from these multi-variate analyses suggest Chl*a*, SST, and PPT are the primary factors correlating with phytoplankton population levels. However, these variables alone are not sufficient to accurately predict HAB formation. Continued investigation will incorporate in-water optical properties toward improving HAB prediction for the northern GOM.

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